

Pressure Profiles in a Loop Heat Pipe under Gravity Influence

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During the operation of a loop heat pipe (LHP), the viscous flow induces pressure drops in various elements of the loop. The total pressure drop is equal to the sum of pressure drops in vapor grooves, vapor line, condenser, liquid line and primary wick, and is sustained by menisci at liquid and vapor interfaces on the outer surface of the primary wick in the evaporator. The menisci will curve naturally so that the resulting capillary pressure matches the total pressure drop. In ground testing, an additional gravitational pressure head may be present and must be included in the total pressure drop when LHP components are placed in a non-planar configuration. Under gravity-neutral and anti-gravity conditions, the fluid circulation in the LHP is driven solely by the capillary force. With gravity assist, however, the flow circulation can be driven by the combination of capillary and gravitational forces, or by the gravitational force alone. For a gravity-assist LHP at a given elevation between the horizontal condenser and evaporator, there exists a threshold heat load below which the LHP operation is gravity driven and above which the LHP operation is capillary force and gravity co-driven. The gravitational pressure head can have profound effects on the LHP operation, and such effects depend on the elevation, evaporator heat load, and condenser sink temperature. This paper presents a theoretical study on LHP operations under gravity-neutral, anti-gravity, and gravity-assist modes using pressure diagrams to help understand the underlying physical processes. Effects of the condenser configuration on the gravitational pressure head and LHP operation are also discussed.

Nomenclature

ATLAS	=	Advanced Topographic Laser Altimeter System
CC	=	compensation chamber
$G_{E,cc}$	=	thermal conductance between the evaporator and reservoir
$G_{vl,a}$	=	thermal conductance between the fluid and ambient along the vapor line
g	=	accelerating force due to gravity
h	=	enthalpy of fluid
ICESat	=	Ice, Cloud, and Land Elevation Satellite
L_{vl}	=	length of the vapor line
LHP	=	loop heat pipe
LTCS	=	Laser Thermal Control System
m	=	mass
\dot{m}	=	total mass flow rate in the loop
\dot{m}_l	=	liquid mass flow rate at the exit of the evaporator
\dot{m}_v	=	vapor mass flow rate at the exit of the evaporator
NASA	=	National Aeronautics and Space Administration
P_1	=	absolute pressure at the outer surface of the primary wick (vapor side of the meniscus)
P_2	=	absolute pressure at the exit of the evaporator
P_3	=	absolute pressure at the inlet of the condenser
P_4	=	absolute pressure at the liquid/vapor interface in the condenser
P_5	=	absolute pressure at the exit of the condenser
P_6	=	absolute pressure at the inner surface of the primary wick

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P_7	=	absolute pressure at the outer surface of the primary wick (liquid side of the meniscus)
P_{cc}	=	absolute pressure at the reservoir
P_E	=	absolute pressure at the evaporator
P_{cond}	=	absolute pressure at the condenser
Q	=	heat load
Q_E	=	heat load applied to evaporator
Q_{leak}	=	heat leak from the evaporator to reservoir
Q_{sub}	=	subcooling of liquid entering reservoir
R	=	radius of curvature of wick pores
S	=	slip ratio
T	=	temperature
T_a	=	ambient temperature
T_{cc}	=	saturation temperature of fluid in reservoir
T_{cond}	=	ambient temperature
T_E	=	evaporator temperature
T_{in}	=	temperature of liquid at the reservoir inlet
ΔH	=	elevation of the condenser above the evaporator
ΔP_{cap}	=	capillary pressure
ΔP_{cond}	=	viscous pressure drop in the condenser
ΔP_g	=	overall gravitational pressure head
ΔP_{gl}	=	gravitational pressure head due to vapor flow in the vapor line
ΔP_{gv}	=	gravitational pressure head due to liquid flow in the liquid line
ΔP_{groove}	=	viscous pressure drop in vapor grooves
ΔP_{ll}	=	viscous pressure drop in the liquid line
ΔP_{vl}	=	viscous pressure drop in the vapor line
ΔP_{tot}	=	total viscous pressure drop
ΔP_{wick}	=	viscous pressure drop in the wick
α	=	vapor void fraction
λ	=	latent heat of vaporization of the working fluid
ρ_l	=	density of liquid of the working fluid
ρ_v	=	density of vapor of the working fluid
$\bar{\rho}$	=	density of the two-phase fluid
θ	=	contact angle
σ	=	surface tension force of the working fluid
x	=	vapor quality

I. Introduction

DURING the operation of a loop heat pipe (LHP), the viscous flow induces pressure drops in various elements of the loop. The total pressure drop is equal to the sum of pressure drops in vapor grooves, vapor line, condenser, liquid line and primary wick. The total pressure drop is sustained by menisci at liquid and vapor interfaces on the outer surface of the primary wick in the evaporator. The menisci will curve naturally so that the capillary pressure developed matches the total pressure drop in the loop [1,2]. In ground testing, an additional gravitational pressure head may be present and must be included in the total pressure drop when LHP components are placed in a non-planar configuration.

Under gravity-neutral and anti-gravity conditions, the fluid circulation in the LHP is driven solely by the capillary force. As long as the total pressure drop is no greater than the capillary capability of the primary wick, the flow circulation can be sustained. With gravity assist, however, the flow circulation can be driven by the combination of capillary and gravitational forces, or by the gravitational force alone. For a gravity-assist LHP at a given elevation between the condenser and evaporator, there exists a threshold heat load below which the LHP operation is gravity driven and above which the LHP operation is capillary force and gravity co-driven.

During the instrument level and spacecraft level testing, very often the LHP is placed in a non-planar orientation, resulting in a gravity-assist mode of operation. In previous LHP ground testing of LHPs, the effect due to gravity assist was not significant and hence did not receive much attention. In recent thermal vacuum testing of the Laser Thermal Control System (LTCS) for ICESat-2 Advanced Topographic Laser Altimeter System (ATLAS),

the gravity-assist LHP which was part of the LTCS, exhibited some unexpected flow and temperature oscillations [3]. The operating temperature and the required reservoir control heater power deviated greatly from analytical predictions. Testing was halted for several months until the root cause of the problem was found and the issue was resolved. Such unexpected LHP behaviors due to gravity assist can have great impacts on flight projects in terms of technical soundness, schedule, and cost. A better understanding of the underlying physical processes involved in the LHP operation with gravity assist is critically needed.

This paper describes a theoretical study on the LHP operation under gravity-neutral, anti-gravity, and gravity-assist modes with an emphasis on the underlying physical processes using corresponding pressure diagrams for illustrations. Effects of the condenser configuration on the gravitational pressure head and LHP operation are also discussed.

Figure 1 shows a flow schematic of an LHP. The LHP reservoir is also referred to as the compensation chamber (CC). If the following discussions, these two terms are used interchangeably.

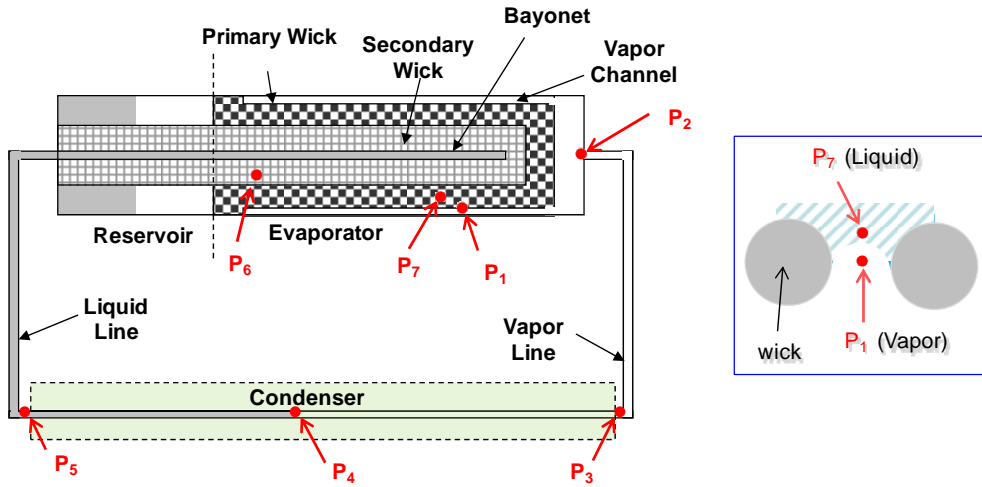


Figure 1. Schematic of an LHP

II. LHP Operation Under Gravity-Neutral Condition

In the normal LHP operation under a gravity-neutral configuration, the total pressure drop to be sustained by the evaporator wick is the sum of viscous pressure drops in vapor grooves, vapor line, condenser, liquid line, and primary wick [1, 2]. This can be expressed as:

$$\Delta P_{\text{tot}} = \Delta P_{\text{groove}} + \Delta P_{\text{vl}} + \Delta P_{\text{cond}} + \Delta P_{\text{ll}} + \Delta P_{\text{wick}} \quad (1)$$

A diagram showing the viscous pressure drops in the loop is shown in Figure 2, where absolute pressures at the corresponding locations shown in Figure 1 are depicted. For simplicity, it is assumed that the evaporator core is an extension of the reservoir. Thus, P_6 is the same as the reservoir saturation pressure. The total pressure drop to be sustained by the primary wick is equal to $P_1 - P_7$, which must not exceed the capillary limit of the primary wick, i.e.

$$\Delta P_{\text{tot}} = P_1 - P_7 \quad (2)$$

$$\Delta P_{\text{tot}} \leq \Delta P_{\text{cap}} \quad (3)$$

where,

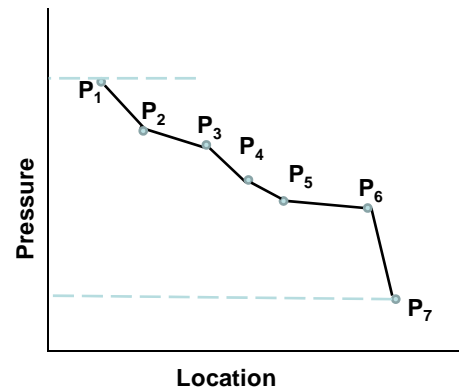


Figure 2. Pressure Profile for Gravity-Neutral LHP Operation

$$\Delta P_{\text{cap}} = 2\sigma \cos\theta / R \quad (4)$$

The reservoir saturation pressure governs the loop operation, and all other absolute pressures are related to the reservoir pressure through their respective pressure drops. Thus, the absolute pressures shown in Figure 2 will move up or down with the rise and fall of the reservoir saturation temperature. An additional gravitational pressure head will certainly affect the reservoir saturation temperature and all of the absolute pressures. On the other hand, it is the pressure drops among LHP elements that are of most interest in the present discussion. The dependence of the pressure drop between any two LHP elements as a function of temperature is mainly due to changes in density and viscosity of the liquid and vapor phases. This is usually a secondary effect. In the following discussions of gravity effect and presentations of pressure diagrams, the change in pressure drop due to the change in temperature will be neglected.

There are three locations in the LHP where the working fluid is in a two-phase state: reservoir, evaporator, and condenser. When the working fluid exists as a two-phase fluid, there is a one-to-one correspondence between the saturation temperature and saturation pressure. Therefore, there is a constraint between the pressure difference and temperature difference between any two LHP elements where two-phase fluid exists. Specifically, the following constraints apply to the LHP reservoir, evaporator, and condenser:

$$P_E - P_{cc} = (dP/dT) (T_E - T_{cc}) \quad (5)$$

$$P_E - P_{\text{cond}} = (dP/dT) (T_E - T_{\text{cond}}) \quad (6)$$

$$P_{\text{cond}} - P_{cc} = (dP/dT) (T_{\text{cond}} - T_{cc}) \quad (7)$$

In Figures 1 and 2, the working fluid flows from the evaporator to the condenser and returns to the reservoir, therefore, $P_1 > P_4 > P_6$, and $T_E > T_{\text{cond}} > T_{cc}$.

III. LHP Operation Under Anti-Gravity Orientation

When the LHP is placed in a anti-gravity position in a gravity field, i.e. the condenser is below the evaporator, an additional pressure head due to gravity must be added to the total pressure drop, i.e.

$$\Delta P_{\text{tot}} = \Delta P_{\text{groove}} + \Delta P_{\text{vl}} + \Delta P_{\text{cond}} + \Delta P_{\text{ll}} + \Delta P_{\text{wick}} - \Delta P_g \quad (8)$$

and,

$$\Delta P_g = (\rho_l - \rho_v)g\Delta H \quad (9)$$

where ΔH is the difference in heights measured from the condenser to the evaporator in the gravity field, and is positive when the condenser is above the evaporator and negative when the condenser is below the evaporator.

Assuming the entire condenser is on a horizontal plane, the pressure profile for the anti-gravity LHP operation is shown in Figure 3, where the pressure profile under the gravity-neutral LHP operation (in black) shown in Figure 2 is kept for comparison, and those new pressures affected by gravity are shown in blue.

As the vapor flows along the vapor line and downward toward the condenser, viscous effect lowers the vapor pressure but the gravitational effect increases the vapor pressure. At the inlet to the condenser, P_3' is higher than P_3 by an amount equal to the gravitational pressure head, ΔP_{gv} :

$$\Delta P_{gv} = \rho_v g \Delta H \quad (10)$$

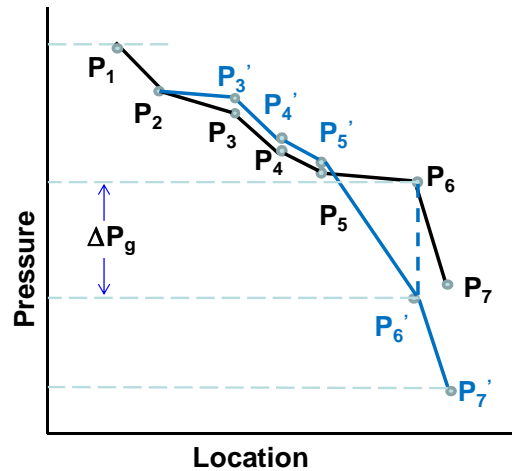


Figure 3. Pressure Profile for Anti-Gravity LHP Operation

For a horizontal condenser, the gravitational pressure head remains the same. Hence, P_4' is higher than P_4 by ΔP_{gv} , and P_5' is higher than P_5 by ΔP_{gv} , assuming that the viscous pressure drops remain unchanged. As the liquid flows along the liquid line and upward toward the reservoir, the liquid pressure decreases due to the gravitational pressure head in addition to the viscous effect. At the inlet to the reservoir, P_6' is lower than P_5' by an amount equal to ΔP_{gl} :

$$\Delta P_{gl} = \rho_l g \Delta H \quad (11)$$

Combining ΔP_{gv} and ΔP_{gl} , the net effect due to gravity is an increase of the total pressure drop of ΔP_g represented by Equation (6) and shown in Figure 3 as the difference between P_6 and P_6' . Under this mode of LHP operation, $P_1 > P_4' > P_6'$, and $T_E > T_{cond} > T_{cc}$. Furthermore, the difference between the condenser temperature and reservoir temperature increases in order to sustain the additional pressure head exerted to the condenser by gravity.

Figure 3 can become complex to visualize. A simplified pressure diagram is given in Figure 4 where ΔP_{gv} is ignored between P_2 and P_5 and the net gravitational pressure head ΔP_g , a vertical dash line, is added to P_6 . This will make discussions much easier and still yield the same effect on the total pressure drop. This approach of adding the net gravitational pressure head to the liquid line will be used in all of the following discussions.

In Figure 4, the total pressure drop ($\Delta P_{tot} = P_1 - P_7'$) is increased by ΔP_g compared to that without gravity. Hence, the heat transport capability of the LHP is decreased. When ΔH becomes too large so that ΔP_g is greater than the capillary capability of the wick, the LHP will not be able to transport any heat load.

The gravitational pressure head also causes the pressure difference between the evaporator and reservoir ($P_1 - P_6'$) to increase. This in turn causes a greater temperature difference between these two elements, resulting in a higher heat leak from the evaporator to reservoir. However, the mass flow rate and the subcooling carried by the liquid returning to the reservoir remains almost the same. This is why the natural operating temperature in an LHP under an anti-gravity configuration can be significantly higher than that in a horizontal LHP under otherwise identical operating conditions.

A higher heat leak due to the gravitational pressure head also means a reduction in the reservoir control heater power requirement when the reservoir temperature is actively controlled. This is true under any heat load, but is much more pronounced at low heat loads. In fact, at low heat loads, the natural operating temperature could be higher than the desired set point temperature, rendering the desired reservoir temperature control through cold-biasing unattainable.

During the startup transient, as the vapor flows along the vertical vapor line, ΔP_g continues to increase until the vapor front reaches the inlet of the horizontal condenser and remains the same as long as the vapor front stays inside the condenser. If the condenser is fully utilized and the vapor front moves into the liquid line, ΔP_g will decrease due to a decreasing ΔH .

IV. LHP Operation With Gravity Assist

With gravity assist, the flow circulation in an LHP can be driven by the combination of capillary and gravitational forces, or by the gravitational force alone. For a gravity-assist LHP with a fixed elevation between the condenser and evaporator, there exists a threshold heat load below which the LHP operation is gravity driven and above which the LHP operation is capillary force and gravity co-driven. This threshold heat load serves as the transition heat load between the two modes of LHP operation. The capillary force and gravity co-driven operation will be presented first, followed by the characteristics of the threshold (transition) heat load. The gravity driven operation will be described last.

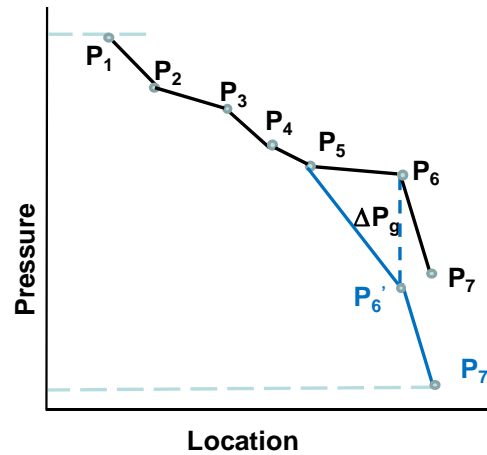


Figure 4. Simplified Pressure Drop Diagram for Anti-Gravity LHP Operation

A. Capillary Force and Gravity Co-Driven LHP Operation

When the heat load to the evaporator is higher than the threshold heat load, the total pressure drop in the LHP is sustained by the capillary pressure. The basic LHP operating principle is no different from that under the gravity-natural configuration except that gravity provides an additional driving force to help the flow circulation. In this manner, gravity-assist LHP operation is the opposite of the anti-gravity LHP operation where the gravitational force presents an additional resistance to the flow circulation. In all three cases, the vapor grooves and vapor line are occupied by 100 percent vapor. Equations (2) to (9) apply to all cases as long as the gravitational pressure head ΔP_g is properly accounted for.

The simplified pressure diagram for capillary force and gravity co-driven LHP operation is shown in Figure 5 where the solid line connecting P_5 and P_6' represents the absolute pressures along the liquid line due to the combined viscous and gravitational effects and the dash line represents the net gravitational effect. The gravitational pressure head raises the reservoir pressure from P_6 to P_6' , and reduces the total pressure drop ($\Delta P_{tot} = P_1 - P_7'$) by ΔP_g when compared to that without gravity assist ($\Delta P_{tot} = P_1 - P_7$). Hence, the heat transport capability of the LHP is increased.

The gravitational pressure head also reduces the delta pressure between the evaporator and reservoir ($P_1 - P_6'$) by ΔP_g . This in turn reduces the heat leak from the evaporator to reservoir due to a reduced temperature difference between these two elements. If the reservoir temperature needs to be actively controlled, the required control heater power will decrease.

B. Threshold Heat Load

In Figure 5, if the condenser is raised to a higher and higher position at a given evaporator heat load, the gravitational pressure head ΔP_g will continue to increase. At some condenser elevation, P_1 will be the same as P_7' , i.e. the total pressure drop to be sustained by the capillary wick, ($\Delta P_{tot} = P_1 - P_7'$), is equal to zero as shown in Figure 6. Conversely, for a given condenser elevation, there is a threshold heat load that results in a zero total pressure drop. At the threshold heat load, the menisci on the outer surface of the wick will be flat as there is no pressure drop imposed upon them. Without any pressure difference to be sustained, the capillary force becomes dormant (inactive). Under such an operating condition, liquid in the evaporator will be vaporized to yield vapor with 100 percent quality, and the vapor will flow along the vapor grooves and vapor line to reach the condenser.

By setting ΔP_{tot} to zero, Equation (8) becomes:

$$\Delta P_g = \Delta P_{groove} + \Delta P_{vl} + \Delta P_{cond} + \Delta P_{ll} + \Delta P_{wick} \quad (12)$$

Equation (12) simply states that the total viscous pressure drop, represented by $P_1 - P_7'$, is completely balanced by the gravitational pressure head. No capillary pressure is needed. Note that $P_6' > P_1$, and hence the liquid is evaporated inside the evaporator at a lower temperature than the reservoir saturation temperature. It also implies that there is no heat leak from the evaporator to the reservoir through the fluid inside the evaporator.

Because the gravitational pressure head and the viscous pressure drop in each component of the LHP are functions of the temperature, and the LHP operating temperature is a function of the heat load, the threshold heat load cannot be obtained directly from equation (12). The threshold heat load and the loop operating temperature

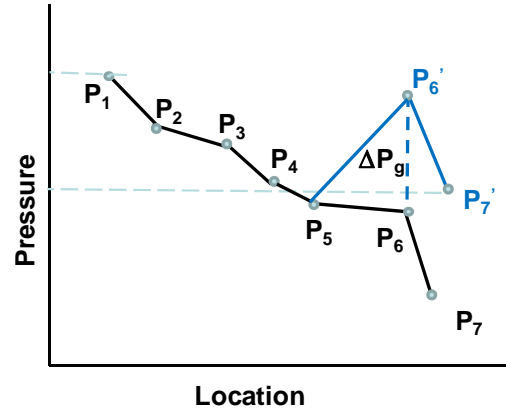


Figure 5. Simplified Pressure Drop Diagram in LHP in Capillary Force and Gravity Co-Driven Mode

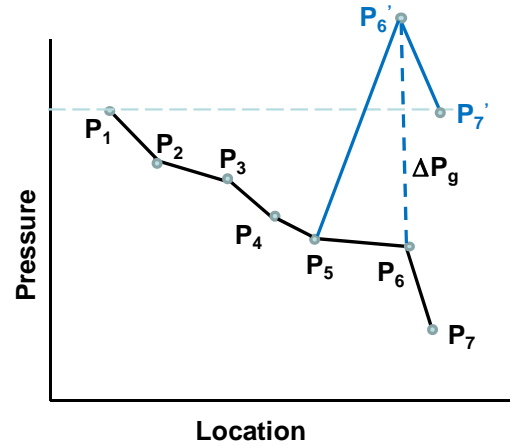


Figure 6. Simplified Pressure Drop Diagram in LHP with Gravity Assist at the Threshold Heat

must be determined simultaneously. This can be done by making initial guesses and going through an iterative process until the final solutions are obtained.

C. Gravity-Driven LHP Operation

In Figure 6, when the condenser is raised to an even higher position, the gravitational pressure head ΔP_g will become larger than the total viscous pressure drop in the LHP at the given evaporator heat load. The absolute pressure on the liquid side of the menisci of the wick will be higher than that on the vapor side, i.e. $P_7' > P_1$, as shown in Figure 7. The gravitational force will cause liquid to be injected into the vapor grooves, and the nature of the fluid flow in the LHP will be completely different from that driven by the capillary force alone or that co-driven by the capillary and gravitational forces. First, there is a liquid mass flow rate induced by the gravity in addition to the vapor mass flow rate generated by the liquid evaporation inside the evaporator. Second, two-phase fluid instead of pure vapor will flow along vapor grooves and the vapor line. The vapor quality and vapor void fraction of the two-phase flow are mainly functions of the gravitational pressure head (the elevation), evaporator heat load and condenser sink temperature. Third, the total mass flow rate, the gravitational pressure head, and the viscous pressure drop in each LHP component are functions of the operating temperature, which is not known a priori. Hence, the liquid mass flow rate and the operating temperature must be solved simultaneously from the governing equations.

Because the capillary force is no longer involved and the gravitational force becomes the sole driving force for the fluid flow, Equation (12) still applies. However, Equation (9) must be modified as:

$$\Delta P_g = (\rho_l - \bar{\rho}) g \Delta H \quad (13)$$

And Equation (12) becomes:

$$(\rho_l - \bar{\rho}) g \Delta H = \Delta P_{\text{groove}} + \Delta P_{\text{vl}} + \Delta P_{\text{cond}} + \Delta P_{\text{ll}} + \Delta P_{\text{wick}} \quad (14)$$

where $\bar{\rho}$ is the density of the two-phase fluid,

$$\bar{\rho} = \rho_v \alpha + \rho_l (1 - \alpha) \quad (15)$$

$$\alpha = \frac{x \rho_l}{[x \rho_l + (1-x) \rho_v S]} \quad (16)$$

The slip ratio, S , depends on the flow pattern of the two-phase fluid. The total mass flow rate in the loop can be expressed as:

$$\dot{m} = \dot{m}_v + \dot{m}_l \quad (17)$$

The vapor mass flow rate at the exit of the evaporator is proportional to the heat load applied to the evaporator at steady state.

$$\dot{m}_v = \frac{Q_E - Q_{\text{leak}} - Q_{\text{sub}}}{\lambda} \quad (18)$$

Although the reservoir saturation temperature is higher than the vapor temperature in the evaporator, a heat leak from the evaporator to the reservoir can still occur through the envelope structure of the evaporator and reservoir assembly.

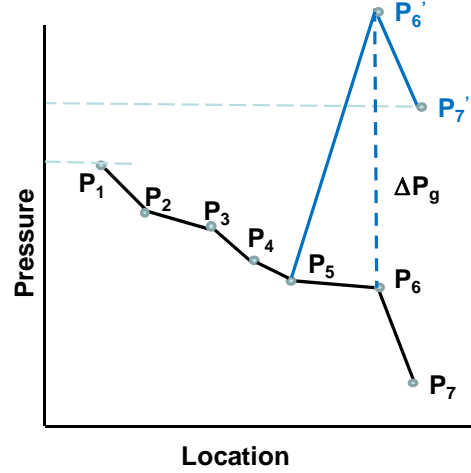


Figure 7. Pressure Drop Diagram in a Gravity Driven LHP

$$Q_{leak} = G(T_E - T_{cc}) \quad (19)$$

The subcooling carried by the liquid entering the reservoir can be expressed as:

$$Q_{sub} = \dot{m}C_p(T_{cc} - T_{in}) \quad (20)$$

Because the viscous pressure drop in each LHP component is directly related to the total mass flow rate, the liquid mass flow rate at the exit of evaporator will naturally adjust itself so as to satisfy Equations (14) and (17) simultaneously.

The working fluid is in the two-phase state along the vapor line, and hence the heat transfer between the fluid and the ambient is in the form of latent heat. The energy equation along the vapor line can be expressed as:

$$-\dot{m} \frac{dh}{dL} = \frac{G_{vl,a}}{L_{vl}} (T - T_a) \quad (21)$$

Equations (14) to (21) are governing equations for mass, momentum, and energy conservations for fluid flow around the loop under gravity-driven mode of the LHP operation. The pressure drop and heat transfer in various components can be obtained using well-known correlations. Note that, with a fixed heat load applied to the evaporator, the liquid mass flow rate at the exit of the evaporator is initially unknown because the gravitational pressure head and the viscous pressure drop in each component are strongly dependent upon the liquid mass flow rate. An iterative process is required to obtain the steady state operating temperature and the liquid mass flow rate at the exit of the evaporator simultaneously.

Analytical models for LHP operation under the gravity-driven mode are highly desirable and yet to be developed. Such a computer model can be obtained by modifying existing computer models which predict the gravity-neutral LHP behaviors [4-8]. The first step in developing the gravity-driven computer model is to find the threshold heat load. For a given set of the condenser elevation and condenser sink temperature, an iterative process is needed to obtain the threshold heat load and the operating temperature.

The next step is to compare the given evaporator heat load to the threshold heat load under the same condenser elevation and condenser sink temperature. If the evaporator heat load is greater than the threshold heat load, the LHP is operating under the capillary force and gravity co-driven mode and the operating characteristics are basically the same as that under the gravity-neutral mode of operation except that the gravitational pressure head must be added to the total pressure drop. If the evaporator heat load is small than the threshold heat load under the same condenser elevation and condenser sink temperature, the LHP is operating under the gravity-driven mode. Another iterative process is required to obtain the LHP operating temperature and the liquid mass flow rate at the exit of the evaporator simultaneously using Equations (14) through (21) and taking into account the fluid state in various components of the LHP.

V. Reverse Liquid Flow

For LHP operations requiring reservoir set point temperature control, the most commonly used method is to use cold biasing and electrical heaters on the reservoir [9]. There is an upper limit on the reservoir control heater power in using this approach. If the rate of temperature increase of the heat source (or simulated thermal mass) is greater than that of the reservoir, i.e. $(Q/mC_p)_{TM} > (Q/mC_p)_{RES}$, the thermal mass temperature will be able to rise with the reservoir temperature and the reservoir set point temperature can be raised smoothly. If the rate of temperature increase of the reservoir is much greater than that of the thermal mass, i.e. $(Q/mC_p)_{RES} \gg (Q/mC_p)_{TM}$, a reverse liquid flow along the liquid line will occur. If the reservoir continues to be heated with the full control heater power, the loop will eventually be shut down. In fact, this is the mechanism most commonly used to shut down the LHP.

Figure 8 shows the pressure diagram for the LHP operation under a gravity-neutral configuration with a

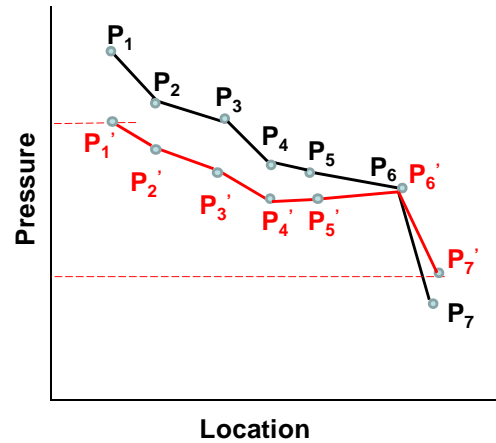


Figure 8. Pressure Drop Diagram with Reverse Liquid Flow for Gravity-Neutral LHP Operation

reverse liquid flow along the liquid line such as that occurs during the transient of the LHP shutdown. The curve in black represents the pressure profile during the normal forward mode of LHP operation (same as that in Figure 2), whereas the curve in red represents the pressure profile during the transient with a reverse liquid flow along the liquid line. Because of its transient nature, the curve in red is a snapshot of the pressures at a given instant. Furthermore, because the reservoir temperature is rising, P_6' is higher than P_6 . In Figure 8, P_6' is purposely laid over P_6 so that the pressure distributions (shapes of the two curves) during the normal operation and the transient operation with reverse liquid flow can be compared. During the transient of LHP shutdown, the forward vapor flow along the vapor line and the reverse liquid flow along the liquid line will co-exist. As the reservoir temperature is rising faster than the thermal mass and evaporator temperatures, the net heat load to the evaporator is decreasing. Thus, P_6' is rising faster than P_1' , and P_7' is moving closer to P_6' due to a smaller mass flow rate through the primary wick. At some point P_7' will be equal to P_1' , and there is no forward flow in the vapor line and no pressure differential across the meniscus for the primary wick to sustain. The next event is an injection of liquid from the reservoir to the evaporator and the flooding of liquid over the entire loop. This is the exact mechanism of LHP shutdown.

Figure 9 shows the pressure diagram of the LHP operation with reverse liquid flow along the liquid line in the anti-gravity mode. The red curve is a snap shot of the pressure distribution in the loop at a given instant and P_6' is purposely laid over the same point during the normal operation under the anti-gravity mode so that the shapes of the two curves can be compared. As the reservoir temperature rises faster than the evaporator temperature, the net heat load to the evaporator is decreasing and the slopes of the pressure drops from P_1' to P_4' become less and less steep. Because P_6' is rising faster than P_1' and P_7' is moving closer to P_6' , P_7' will eventually exceed P_1' and the loop will be shut down. It requires more energy to the reservoir (longer time at the same control heater power) to shut down the loop under the anti-gravity mode than under the gravity-neutral mode due to the ever-present gravitational pressure head acting against the reservoir.

Figure 10 depicts the pressure diagram of the LHP operation with reverse liquid flow along the liquid line in the gravity-assist mode. The red curve is a snap shot of the pressure distribution in the loop at a given instant and P_6' is purposely laid over the same point during the normal operation under the gravity-assist mode so that the shapes of the two curves can be compared. The above-mentioned explanations on the pressure distributions still apply in this case. Because of the gravitational pressure that is favorable to the reservoir, it takes less energy to the reservoir to shut down the loop under the gravity-assist mode than under the gravity-neutral mode.

VI. Vertical Condenser

In the above discussions, it is assumed that the entire condenser is on a horizontal plane. For a horizontal condenser, pressures in the condenser, such as P_4 and P_5 depicted in Figure 2, can be determined without much difficulty even for some complex condenser designs. For a vertical condenser, however, the location of the vapor front inside the condenser is a function of the net heat load to the evaporator and/or the condenser sink temperature. Thus, ΔH in Equations (9) will vary. The key to calculate ΔP_g is to find the net ΔH , which is the vertical distance between the location of the vapor front in the condenser and the location of the evaporator as shown in Figure 11.

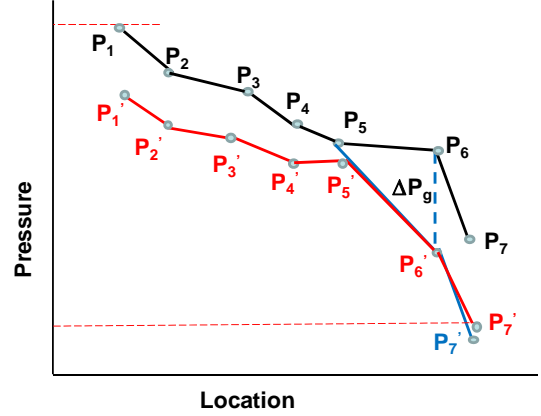


Figure 9. Pressure Drop Diagram with Reverse Liquid Flow for Anti-Gravity LHP Operation

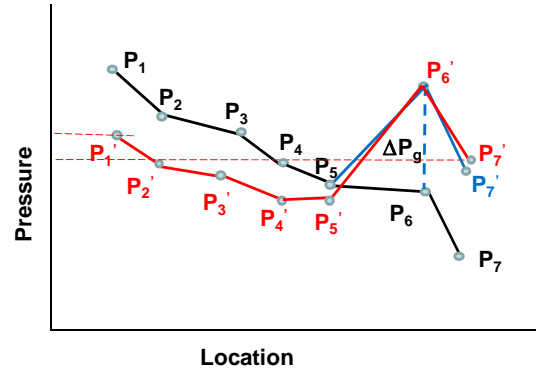


Figure 10. Pressure Drop Diagram with Reverse Liquid Flow for Gravity-Assist LHP Operation

Condenser Plate

Vapor Line

Gravity

Liquid Line

Vapor Front

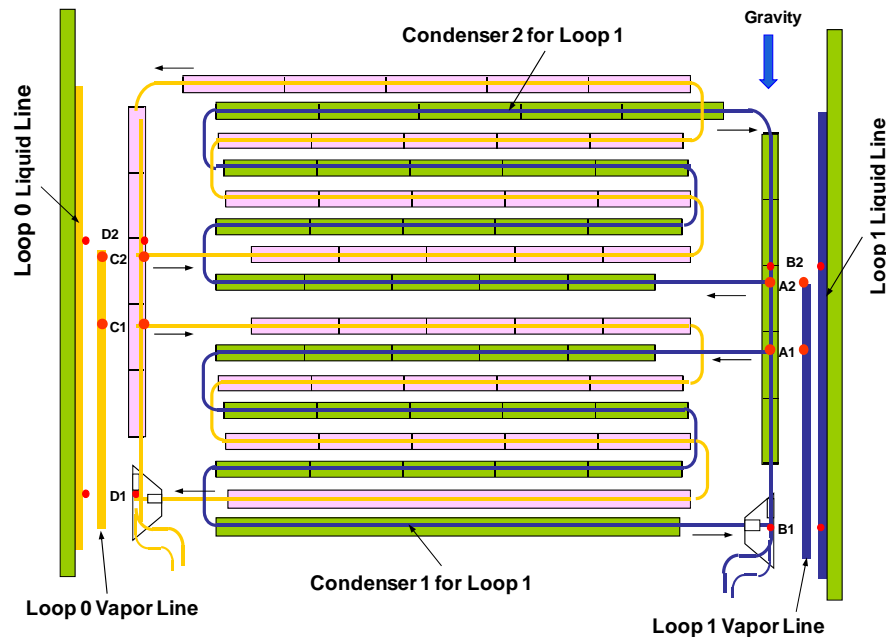
Condenser

Evaporator

Reservoir

ΔH

Figure 13 depicts a schematic of the radiator/condenser design for the LHPs used for thermal control of the Burst Alert Telescope on the Swift spacecraft [10, 11]. Two independent LHPs are used to cool the same instrument, and both share the same radiator. Furthermore, each LHP has two parallel condensers have multiple horizontal and vertical legs. In Figure 13, the green elements represents the LHP 1 condenser. Vapor enters the condenser along the vertical vapor manifold, then splits and enters the two parallel condensers at points A1 and A2. Within each



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condenser, the fluid flows through horizontal and vertical legs. In ground test, gravity causes vapor to enter the upper condenser first. Furthermore, the upper condenser almost has to be fully utilized before the lower condenser will start dissipating heat.

It is much more difficult to perform analytical predictions for LHPs with complex condenser designs involving multiple horizontal and vertical legs. The mass, momentum and energy conservation equations must be solved. But the momentum balance involves a gravitational pressure head term that varies with the height of the vapor front in the condenser while this height must be determined so as to satisfy the energy balance. This is especially true when the vapor front reaches the intersection of the horizontal and vertical legs because the vapor front may move back and forth between the vertical and horizontal legs during successive numerical iterations and the equilibrium position for the vapor front may never converge.

VII. Summary

Governing equations are presented to describe the LHP operation under gravity-neutral, anti-gravity, and gravity-assist modes of operation. The underlying physical processes are described using corresponding pressure diagrams for illustration. In a gravity-neutral environment, the capillary pressure is the sole driving force to sustain the fluid flow in the loop. The fluid is 100 percent vapor in the vapor grooves and vapor line, 100 percent liquid in the liquid line, and two-phase in the condenser. The reservoir saturation temperature, which dictates the loop operating temperature, is affected by the heat load, condenser sink temperature and the ambient temperature.

For a given elevation of the condenser above the evaporator in the gravity-assist mode of LHP operation, there exists a threshold (transitional) heat load above which the LHP operation is capillary force and gravity co-driven and below which the LHP operation is gravity-driven. At the threshold heat load, the fluid is 100 percent vapor in vapor grooves and vapor line, two-phase in condenser, and 100 percent liquid in liquid line and wick. The total viscous pressure drop is exactly balanced by the gravitational pressure head. The threshold heat load and the loop operating temperature must be obtained simultaneously through an iterative process.

The LHP operations under the capillary force and gravity co-driven mode as well as the anti-gravity mode are basically the same as that in the gravity-neutral mode. The only difference is the presence of the gravitational pressure head, which adds an additional flow impedance in the anti-gravity mode, and provides additional driving force for the fluid flow in capillary force and gravity co-driven mode.

When the LHP is operating under a gravity-driven mode, the gravitational pressure head is greater than the sum of the viscous pressure drops in the LHP elements. The principle of momentum balance requires an additional liquid mass flow rate in the loop. The additional liquid mass flow rate will self-adjust so as to satisfy the mass, momentum and energy balance in the LHP operation. The additional liquid mass flow rate and the loop operating temperature are related, and must be found simultaneously by solving the governing equations. Under the gravity-drive mode, the capillary force in the wick becomes inactive. The working fluid is in the two-phase state in vapor grooves, vapor line and condenser, and is 100 percent liquid in the liquid line and capillary wick. Thus, different correlations are required regarding the pressure drop in vapor grooves and vapor line. Additional energy balance equations are also needed for fluid flow along the vapor line. Again, an iterative procedure is required in order to find the reservoir saturation temperature and the total mass flow rate in the loop.

The gravitational pressure head can affect the mode of LHP operation and the LHP behaviors in many ways: 1) it affects the heat transport limit of the LHP; 2) it affects the heat leak from the evaporator to the reservoir, and hence the reservoir saturation temperature or the reservoir control heater power requirement. This is especially true at low evaporator heat loads; 3) it affects startup transients; 4) it affects the flow distribution among multiple, parallel condensers, depending on the condenser configuration and test orientation; 5) it makes the LHP inoperable when the gravitational pressure head alone is greater than the capillary capability of the primary wick under the anti-gravity mode; and 6) it may cause oscillations of the fluid flow and reservoir saturation temperature under certain conditions in the gravity-assist mode.

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